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An Assessment of

the SEA Multi-Element Sensor for Liquid Water Content Calibration of the NASA GRC Icing Research Tunnel

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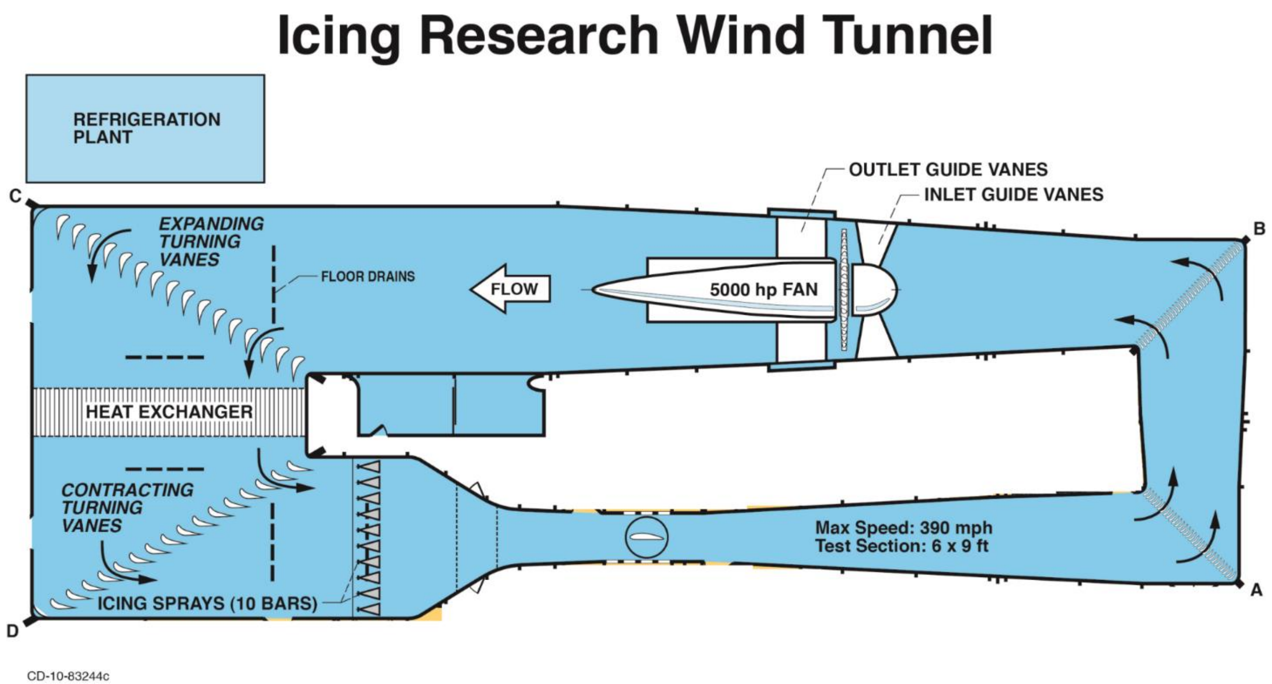
Introduction:

- The NASA Glenn Icing Research Tunnel (IRT) is a facility that is heavily utilized for development/certification of aircraft ice protection systems and icing research.
  - Data from the IRT has been accepted by the FAA, EASA, CAA, and JAA in support of manufacturers' icing certification programs.
- The IRT had been using an Icing Blade technique to measure cloud liquid water content since 1980.
- The IRT conducted testing with Multi-Element sensors from 2009 to 2011 to assess performance. These tests revealed that the Multi-Element sensors showed some significant advantages over the Icing Blade.
- Results of these and other tests are presented here.

Outline:

- Facility Description (IRT)
- Description of the Multi-Element Sensor
  - Components
  - Physics (theory of operation)
  - Processing Multi-Element data
- Description of the Blade
  - Measurement Principles
  - Ludlam Limit
- Comparisons of Multi-Element Sensor to Blade
  - Varying water content
  - Varying speed
  - Varying drop size (Large drops, SLD)
- Conclusions:
  - Strengths of Blade
  - Limitations of Blade
  - Strengths of Multi-Element
  - Limitations of Multi-Element

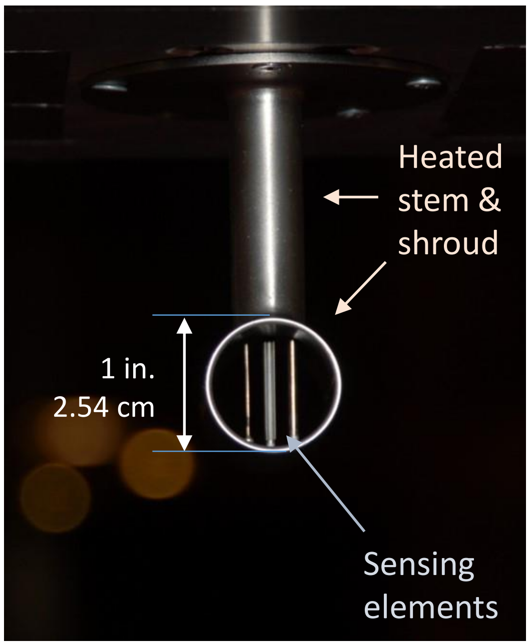
Test Facility



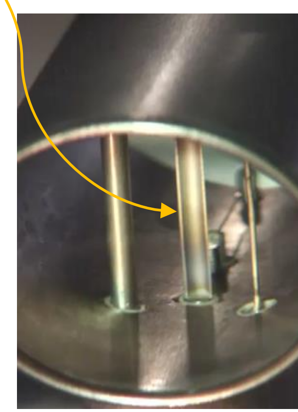
- **Test section size: 6 ft. x 9 ft. (1.8 m x 2.7 m)**
  - All LWC & MVD calibration measurements are made in the center of the test section
  - LWC uniformity is ±10% for the central 4 ft x 6ft
- **Calibrated test section airspeed range: 50 – 325 kts**
- **Air temperature: -40 degC static to +20 degC total**
- **Calibrated MVD range: 14 – 270 µm**
- **Calibrated LWC range: 0.15 – 4.0 g/m³ (function of airspeed)**
- **Two types of spray nozzles:**
  - Standards = higher flow rate
  - Mod1 = lower flow rate

The Multi-Element Sensor

From Science Engineering Associates, Inc.



- Commonly known as “the Multi-Wire”
- Typical Multi-Wire shrouds contain 3 sensing elements of various sizes
  - Different element types are designed for better response to different conditions
  - Elements vary in diameter and in shape
  - IRT typically uses just the TWC element for LWC calibration
- A compensation wire is located behind central element
  - Shielded from impinging liquid/ice water
  - measures changes coming only from airspeed, air temperature, air pressure, and relative humidity



Multi-Element Sensor Theory of Operation

- A voltage is applied across each of the elements to maintain them at a temperature of 140 degC
    - Elements are cooled by convection and impinging water
- Data system records the power required to maintain each element at constant temperature.
- The compensation wire is shielded to stay dry
    - Changes in the comp wire during a spray are reflected in the calculated water content
- The recorded powers are used to calculate liquid water content:

$$P_{elem,wet} = P_{elem,tot} - \underbrace{(\mathit{offset} + \mathit{slope} * P_{comp,dry})}$$

Subtract off cooling from dry air, correlated to comp wire

Conversion factor

$$LWC = \frac{P_{elem,wet}(watts) * 2.389 \times 10^{5}}{\underbrace{\left[L_{evap}\frac{cal}{g} + 1.0\frac{cal}{g * {}^{0}C}\left(T_{evap} - T_{ambient}\right)\right]} * \underbrace{TAS\frac{m}{s} * l_{elem}mm * w_{elem}mm}}$$

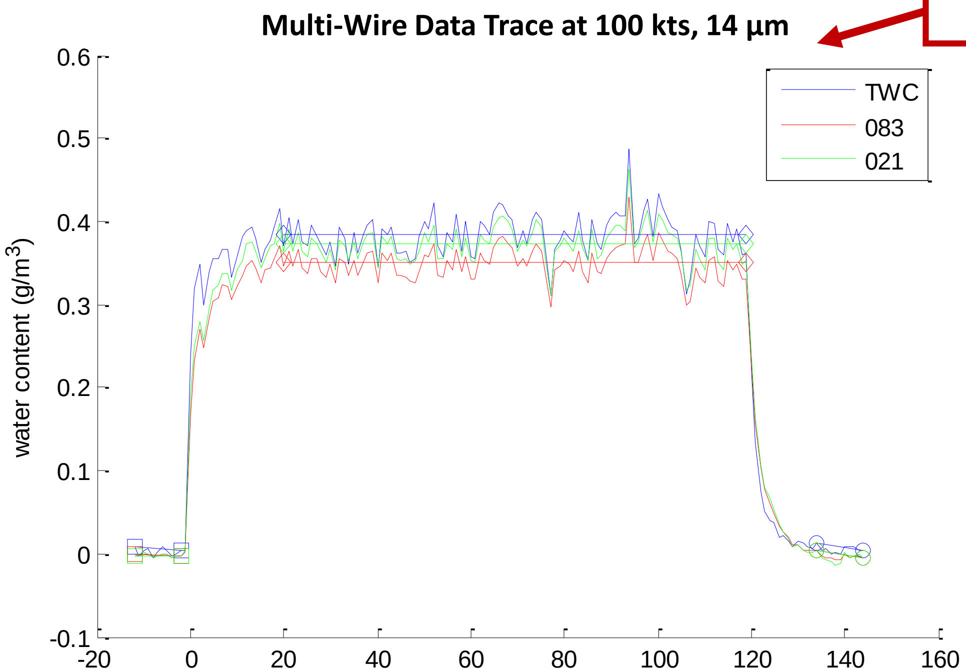
Amount of energy required to raise the drop temp to evaporative temperature and then evaporate it (cal/g)

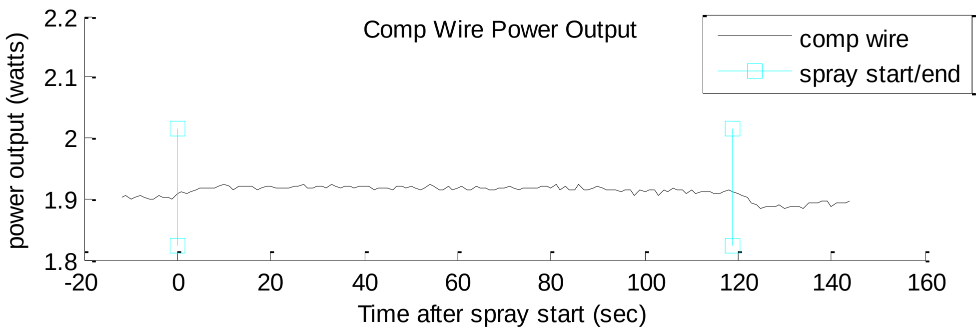
Sample volume of sensing element (m^3/s)

Source: the SEA User’s Manual

Multi-Wire Data Processing

Multi-Wire data trace, showing all 4 sensing elements



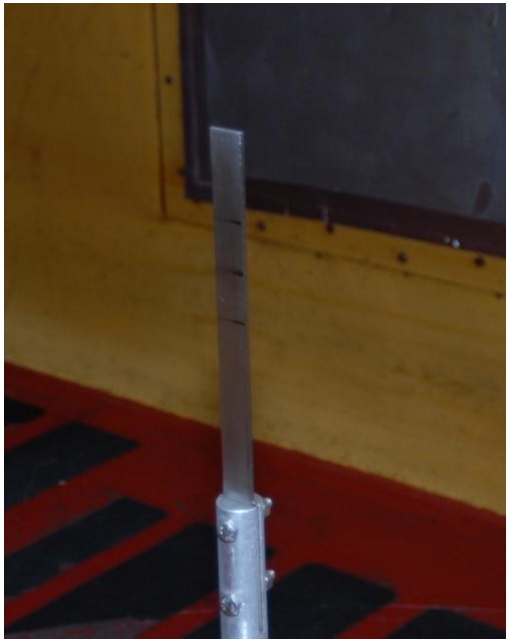


Multi-Wire Data processing:

- IRT uses only the water content values from the TWC element
  - *A comparison of the different elements is beyond the scope of this presentation*
- In-house MATLAB code averages and tares the recorded values
  - Code also flags data irregularities
- Measured TWC is corrected for collection efficiency*

**3D collection efficiency: Rigby, D.L., Struk, P.M., and Bidwell, C., "Simulation of Fluid Flow and Collection Efficiency for an SEA Multi-Element Probe," 6th AIAA Atmospheric and Space Environments Conference, AIAA-2014-2752, 2014.*

The Icing Blade



- Simple piece of stainless steel: 1/8" x 6" x 3/4"
  - 3.175 mm x 154.2 mm x 19.05 mm
- Was the standard measurement for all LWC calibrations in the IRT from 1980 to 2011
- Ice Accretion: Requires Rime Ice
  - Tunnel total air temp of -18 to -20 degC
  - Adjust spray time to collect approx. 0.15 in. (3.8 mm) of ice. ($12 \leq t \leq 200$ sec)
  - Width of ice is measured (< 0.200 in., or 5mm) to make sure changes in collection efficiency are minimal
- 3 measurements (1 in. apart)—use the median value

$$LWC = \frac{1710 \ * d}{V * t * E_b}$$

$d =$ ice thickness (mm)
$V =$ tunnel airspeed (kts)
$t =$ spray time (sec)
$E_b =$ Collection efficiency (calculated, function of airspeed, air density, & drop size)
$1710 =$ constant—contains unit conversions and an assumed ice density of 0.88

The Ludlam Limit *(for the blade)*

- ***Ludlam Limit*: the supercooled water impingement rate above which not all impinging water will freeze for a given air temperature and airspeed** (impingement rate above which the measured LWC is reduced)
    - Water impingement rate is a function of the airspeed, LWC, & Collection Efficiency
- Stallabrass applied Ludlam's work to derive the Ludlam limit for a 1/10th inch diam. rotating cylinder. We used his data to calculate the limit at -20 degC

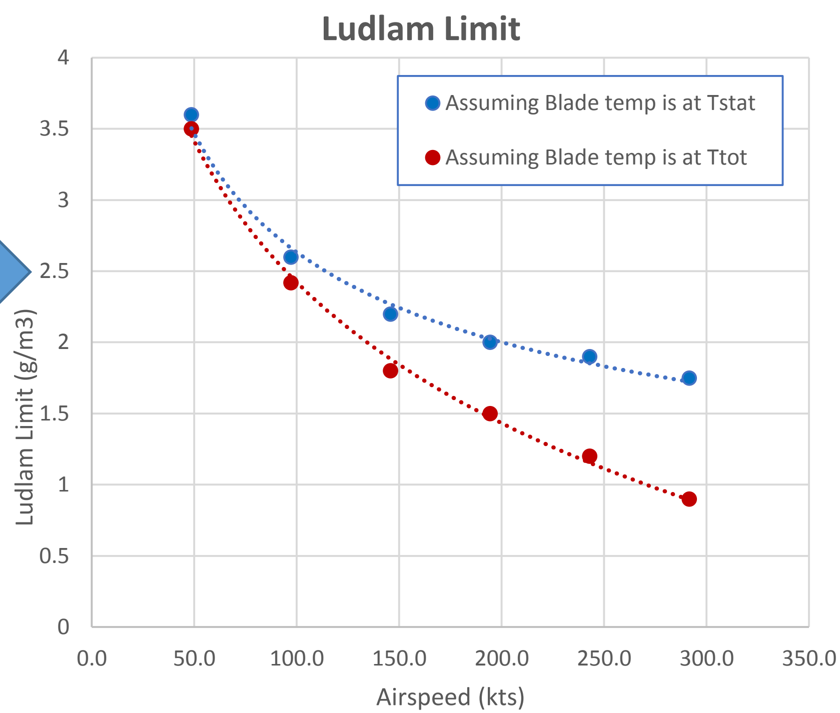


Figure: Ludlam limit as a function of airspeed for a 1/10th inch (2.49 mm) diam. cylinder and two temperature constraints [data from Stallabrass]

Consider: We have a 1/8th in. Blade, not a 1/10th in. rotating cylinder.

- *Collection Efficiency*:
    - We have data that shows the collection efficiency of the 1/8th inch blade is within 2% of that of the 1/10th inch cylinder
- *Temperature*: Stallabrass used static air temperature.
    - In the IRT, icing blade tests are conducted at a total temperature between -18 and -20 degC.
    - The blade temp is somewhere between static and total

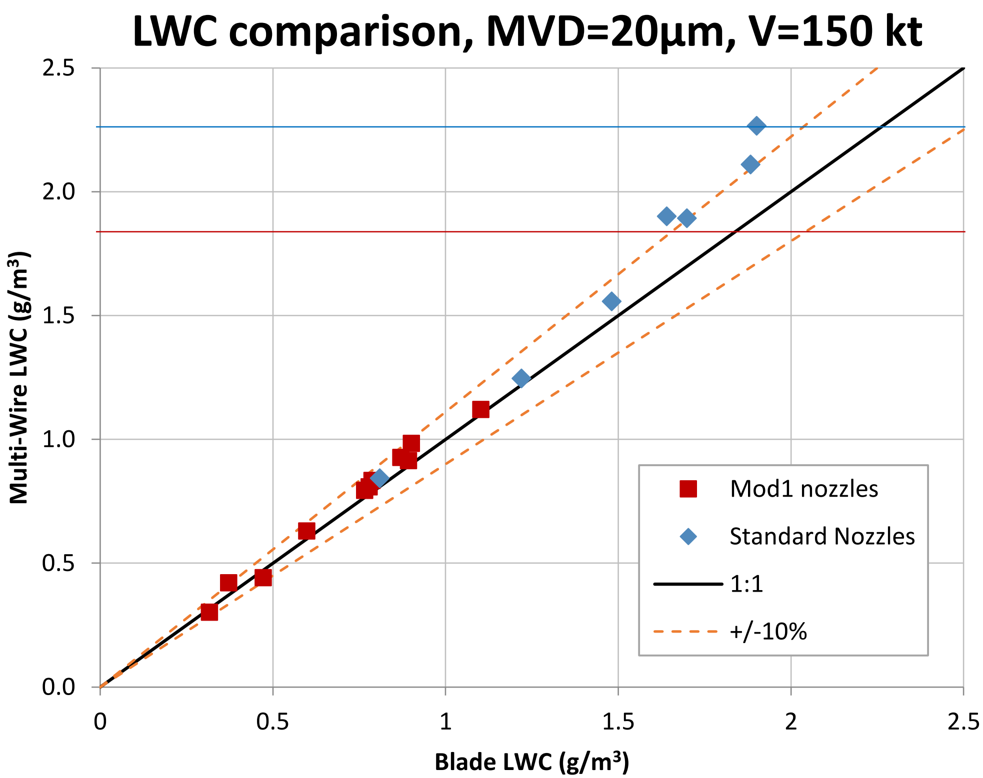
Stallabrass, J. R., "An Appraisal of the Single Rotating Cylinder Method of Liquid Water Content Measurement," National Research Council Canada Internal Report, LTR-LT-92, 1978.

Comparing Multi-Wire vs. Blade

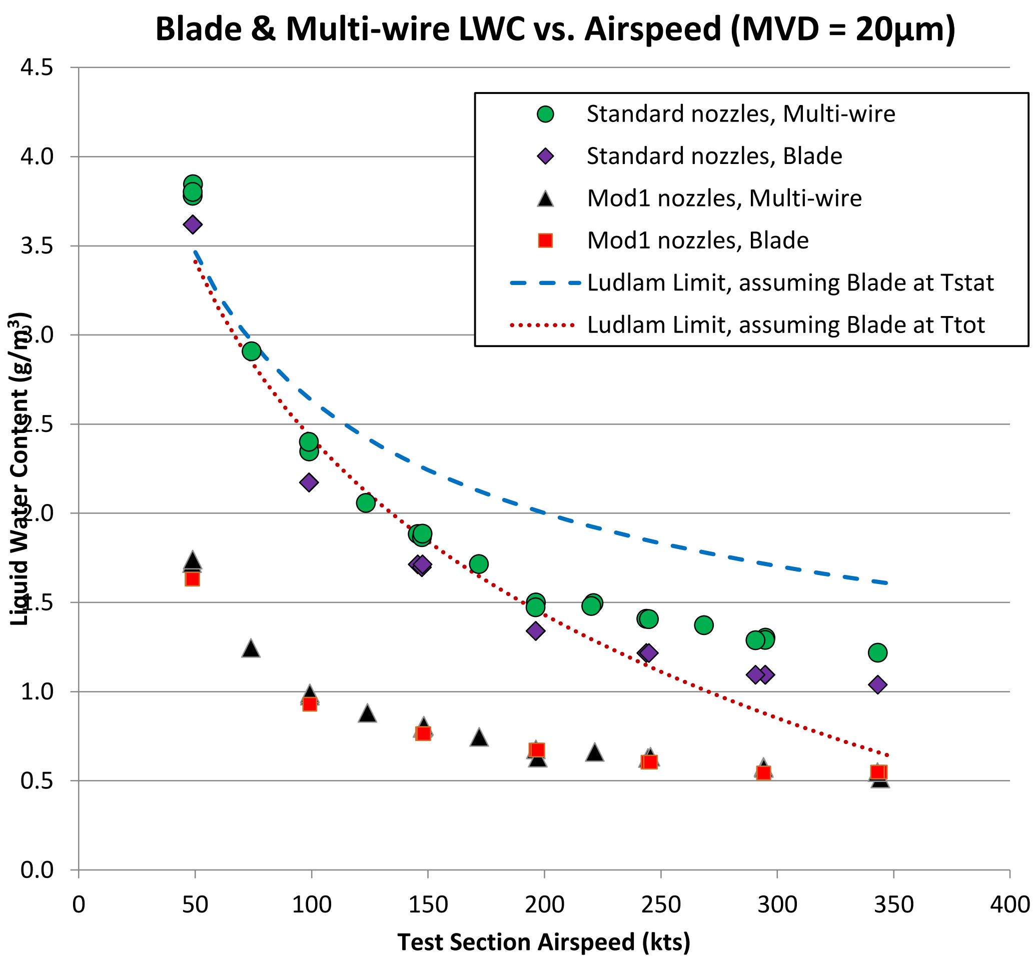
- Thorough comparison had to be done before we could switch LWC calibration instruments.
- The Multi-Wire has obvious advantages over the Blade in terms of:
  - Temperature → the Blade requires hard rime conditions
  - Test efficiency → can collect 30 conditions/day with Blade, vs. 50 conditions/day with Multi-Wire
  - Spray time → not restricted, can capture real-time trends
- We want to see how the two instruments compare, varying:
  - Liquid water content (LWC)
  - Airspeed
  - Drop size (MVD)

Multi-Wire vs. Blade, with respect to **Liquid Water Content**

- For these points:
  - Airspeed = 150 kts
  - MVD = 20 µm
  - T_{tot} = -20 degC (blade)
  - T_{tot} = -10 degC (multi-wire)
- For these conditions, the Ludlam limit is 1.8 g/m^3 if we use the total temp, and 2.2 if we use the static temp.
- This plot shows the water contents match until the LWC approaches or surpasses the Ludlam Limit



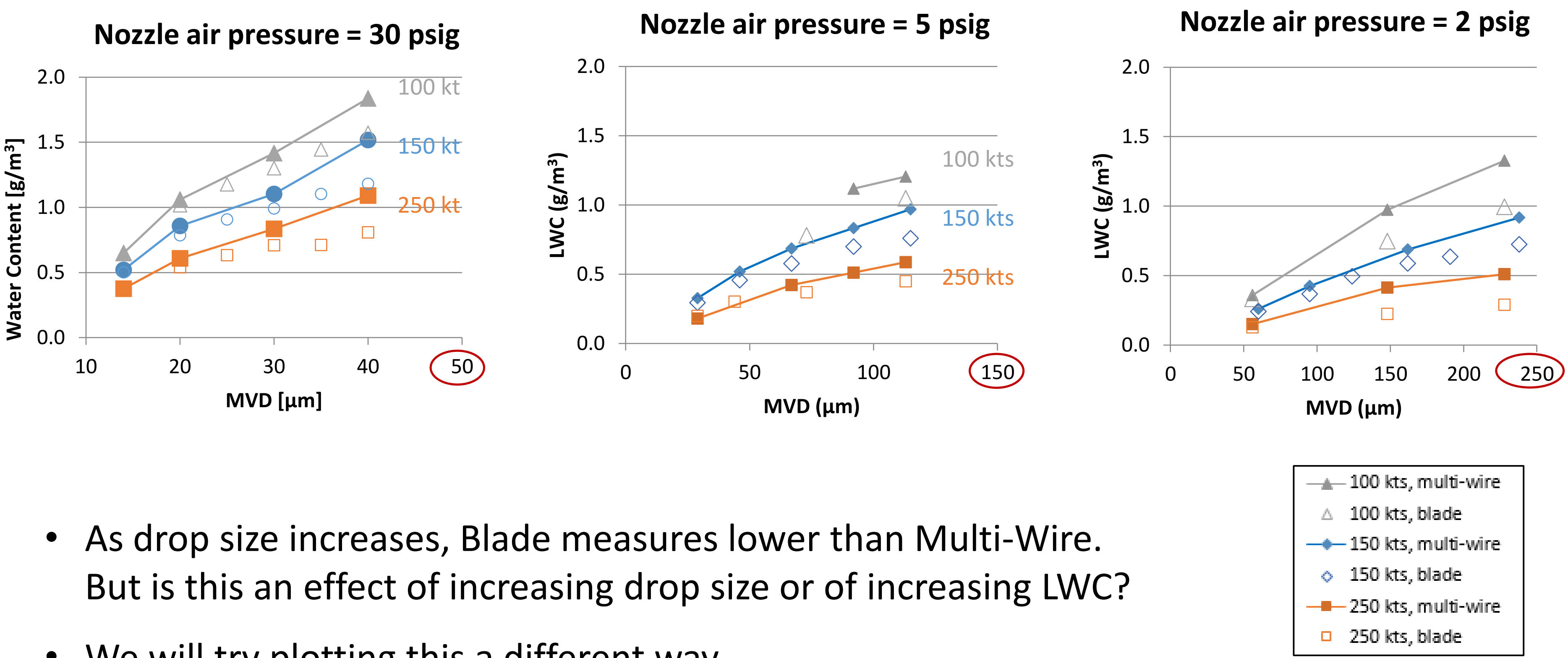
Multi-Wire vs. Blade, with respect to **Airspeed**



- Airspeed sweeps for two nozzle sets, MVD=20µm
  - Standard nozzles are higher water flow, Blade testing requires shorter spray time.
- Plotted alongside Ludlam limit curve fit shown on previous slide
  - Limit for a temperature of -20 degC
- The Mod1 nozzles show good agreement between the MW and the blade, even at high airspeeds
- But at higher impingement rates (LWC x airspeed x Collection Efficiency), the blade measures lower than the MW

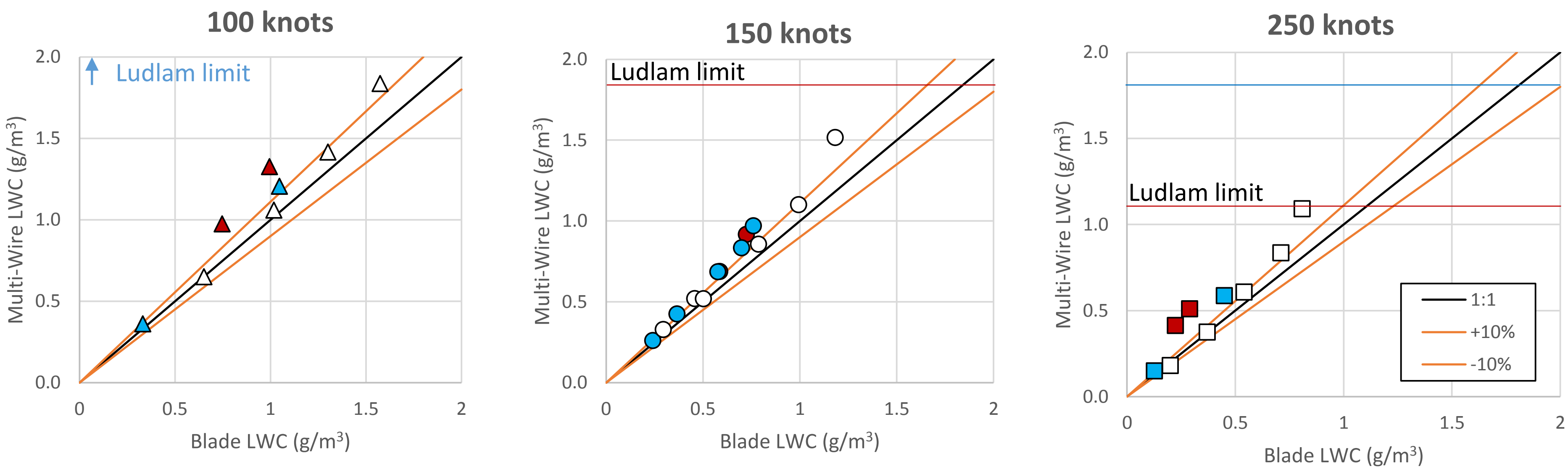
Multi-Wire vs. Blade, with respect to **Drop Size (MVD)**

Multi-wire vs Blade LWC, at 100, 150, and 250 kts



- As drop size increases, Blade measures lower than Multi-Wire. But is this an effect of increasing drop size or of increasing LWC?
- We will try plotting this a different way…

Multi-Wire vs. Blade, with respect to **Drop Size (MVD)** (part 2)



MVD:
- 14 – 50 µm
- 50 – 125 µm
- 125 – 250 µm

- For smaller drop sizes at all velocities, there is an LWC limit at which the Blade measures lower than the Multi-Wire, even for MVD's below 50 µm.
- For larger drop sizes, the Ludlam limit can no longer account for the roll-off we see from the Blade. We suspect that we have an added problem due to mass-loss (splashing?) at larger drop sizes.

Conclusions:

Strengths of Blade

- Simplicity
- Reliability
- Researcher can see the physical ice characteristics

Limitations of Blade

- Does not respond well at higher impingement rates (Ludlam limit)
- Does not respond well at larger drop sizes (suspect mass-loss)

Strengths of Multi-Wire

- Compares well to Blade for most Appendix C conditions
  - MVD ≤ 30 μm
  - Moderate impingement rates
  - Some MW results validated by icing scaling tests in the IRT
- Temperature independent
- Test efficiency
- Spray time independent
- Ability to measure ice crystals *(not addressed in this presentation)*

Limitations of the Multi-Wire

- No limitations of the multi-wire were found from these tests

Questions?

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